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LASER CALIBRATION APPARATUS

The present invention relates to optical apparatus for
measuring deviations of a trajectory from a straight

5   line. More particularly, the invention relates to
optical apparatus for measuring deviations of a
trajectory from a straight line in the movement of a
first machine component relative to a second machine
component. The machine components may be parts of a

10   coordinate positioning apparatus which may comprise,
for example, a machine tool or a coordinate measuring
machine.

Deviations in the movement of a machine component as it

15   moves along a trajectory generally involve rotation of
the component about one or more axes of the machine,
usually referred to as the X,Y and Z axes, and are
referred to as pitch, roll and yaw errors. There are
also errors in straightness of the movement which

20   involve lateral deviations of the machine component
from the main movement axis.

US Patent 4939678 discloses a method of calibrating a
coordinate measuring machine in which laser measuring

25   head is mounted onto a first part of a machine and a
reflecting assembly is mounted on a second part of the
machine. A pair of light beams are transmitted from
the laser measuring head and reflected by the reflector
assembly towards a pair of quad cells in the laser

30   measuring head. The position of the return beams on
these quad cells allows the straightness and roll of
the reflector assembly to be measured. A separate
beam, plane mirror and detector arrangement is used to
measure pitch and yaw. This system only allows 18

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degrees of freedom to be measured.

A first aspect of the present invention provides
apparatus for measuring deviation in the movement of a
5   first body with respect to a second body comprising:
         a transmitter unit mountable on the first body;
         an optic unit mountable on the second body;
         wherein the transmitter unit directs at least one
light beam towards the optic unit;
10   wherein one of the transmitter unit and the optic
unit is provided with two or more detectors to detect
two or more light beams transmitted to or reflected
from the optic unit,
         wherein the optical arrangements for launch and
15   detection of each light beam are substantially the
same.

The launch is the effective start of the light beam and
may comprise, for example, an optical fibre end.
20

Preferably the detectors comprise two-dimensional
arrays of pixels. The detectors may comprise, for
example, charge-coupled devices (CCDs), CMOS sensors or
charge-injection devices (CID).
25

Preferably the optic unit is mounted on a movable body.
The optic unit preferably has no trailing leads which
could cause unwanted movement and affect the accuracy.
Preferably the apparatus also includes linear
30   displacement measuring apparatus, such as an
interferometer. This may comprise a light source in
the transmitter unit to produce a light beam which is
directed to the optic unit, a retroreflector in the
optic unit to reflect the light beam towards the

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transmitter unit, and a fourth detector in the
transmitter unit to detect the returning light beam.

A second aspect of the invention provides apparatus for
5   measuring deviation in the relative movement between a
first body and a second body, the apparatus comprising:
a transmitter unit mountable on the first body and
an optic unit mountable on the second body;
the transmitter unit being provided with one or
10   more detectors and wherein the transmitter unit directs
at least one light beam towards the optic unit;
the optic unit being provided with three
retroreflectors to reflect three beams of light towards
the transmitter unit;
15   wherein the position of the three reflected light
beams on the one or more detectors is used to determine
the deviation of the trajectory from a straight line in
five degrees of freedom.

20   Preferably the five degrees of freedom are pitch, yaw,
roll and straightness along two axes perpendicular to
the axis of movement of the first or second body.

A third aspect of the invention provides apparatus for
25   measuring squareness of the axes of a machine having
first and second parts movable relative to one another,
the apparatus comprising:
a base unit mountable on the first machine part;
a transmitter unit mountable on the base unit, the
30   base unit and at least one surface of the transmitter
unit being provided with cooperating elements to define
the position of the transmitter unit relative to the
base unit in a plurality of known relative orientations
of the transmitter unit and thereby define the

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directions of at least one light beam;

an optic unit mounted on the second machine part;

wherein the transmitter unit directs at least one
light beam towards the optic unit;

5   wherein one of the transmitter unit and the optic
unit is provided with one or more detectors to detect
one or more light beams transmitted to or reflected
from the optic unit;

such that by orientating the transmitter unit
10   along two axes of the base unit and measuring the
deviation of the at least one light beam on the at
least one detector, the squareness of those two axes
can be determined.

15   A fourth aspect of the invention provides apparatus for
measuring deviation in the movement of a first body
with respect to a second body comprising:

a transmitter unit mountable on the first body;

an optic unit mountable on the second body;

20   wherein the transmitter unit directs at least one
light beam towards the optic unit;

wherein one of the transmitter unit and the optic
unit is provided with one or more detectors to detect
one or more light beams transmitted to or reflected
25   from the optic unit;

wherein the position of the light beam on the
detector is used as feedback to adjust the position of
the transmitter unit or change the movement vector of
the second body in order to maintain the light beam on
30   the detector during relative movement of the first and
second bodies.

Embodiments of the invention will now be described by
way of example and with reference to the accompanying

drawings in which:

Fig 1 is a schematic representation of the measuring device mounted on a coordinate measuring machine;

Fig 2 is a plan view of the optical components in the transmitter unit and the optic unit;

Fig 3 is a perspective view of the optical components in both the transmitter unit and the optic unit;

Fig 4 is a plan view of a linear displacement measuring device in the transmitter unit and the optic unit;

Fig 5 is a plan view of a first alternative arrangement of the retroreflectors in the optic unit;

Fig 6 is a plan view of a second alternative arrangement of the retroreflectors in the optic unit;

Fig 7 is a plan view of transmitter unit and the optic unit according to a second embodiment of the invention;

Figs 8A-8C illustrate double reflection on a thin plane optical element, a thick wedged optical element and a thin wedged optical element respectively;

Fig 9 illustrates an optical fibre coupled to a laser light source;

Fig 10 illustrates the optical fibre ends mounted on a bar;

Fig 11 illustrates a clamp used to mount the optical fibre ends of fig 10;

Fig 12A illustrates a spot on the edge of a sensor;

Fig 12B illustrates the spot in fig 12A once a threshold value has been deducted;

Fig 12C illustrates the contours in a spot on the edge of the sensor which are used to calculate the

centroid.

Figs 13A and 13B illustrate alternative optical schemes to fig 2 in which only one or two beams respectively are transmitted;

5   Fig 14 illustrates an optical scheme in which a single detector is used for two light beams;

Fig 15 is a graph of straightness error against distance travelled; and

Figs 16A and 16B illustrated a transmitter unit

10   which is not aligned to a machine axis.

Fig 1 shows the calibration apparatus mounted on a coordinate measuring machine (CMM). A transmitter unit 10 is mounted on the machine table 14 of the CMM. As

15   described in our International Patent Application WO02/04890 the base 18 of the transmitter unit 10 and a base unit 20 mounted on the machine table 14 are provided with complementary parts of a kinematic support 22 which enable the transmitter unit 10 to be

20   accurately aligned along any of the X,Y,Z,-X and -Y axes of the CMM or along any other desired direction. An optic unit 12 is mounted on the quill 16 of the CMM. As also described in International Patent Application No. WO02/04890, the transmitter unit 10 and the optic

25   unit 12 have complementary parts of a kinematic support 24A, 24B such that when they are brought into contact with each other, they become accurately aligned with one another.

30   The transmitter unit 10 is thus mounted on the machine table 14 and aligned with one of the X,Y,Z,-X or -Y axes of the machine or any other desired direction. The optic unit 12 is aligned with the transmitter unit 10 and is mounted on the quill 16 of the machine. The

optic unit 12 and quill 16 are moved along a path in
the direction to which the transmitter unit 10 is
aligned. The apparatus may then be used to measure the
distance of the optic unit 12 from the transmitter unit

5   10 and to measure deviations in the movement of the
optic unit 12 during its movement along this path.

Figs 2-4 show the arrangements of the optical elements
within the transmitter unit 10 and the optic unit 12.

10   A first group of optical elements 26-40 are used as a
linear displacement measuring device, for example an
interferometer, to measure the distance of the optic
unit from the transmitter unit. These are omitted from
Figs 2 and 3 for clarity but are shown separately in

15   Fig 4. Although one particular type of interferometer
will be described this may be replaced by any other
suitable type of linear displacement measuring
apparatus. The interferometer apparatus comprises a
light source 26 in the transmitter unit 10 which

20   produces a light beam 28. A beam splitter 30 splits
the beam 28 and sends a first beam 32 towards a first
retroreflector 36 in the optic unit 12 and a second
beam 34 towards a second retroreflector 38 in the
transmitter unit 10. Both beams 32,34 are reflected

25   by their respective retroreflectors 36, 38 back to the
beamsplitter 30 and on to the detection unit 40. This
interferometer is described in more detail in UK patent
GB2296766.

30   The retroreflectors 36,38 used for the linear
displacement measuring device may comprise existing
retroreflectors in the optic unit (i.e. shared with the
straightness/angular deviation optics), in order to
reduce size and cost. In this case the incident light

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beam may be rotationally displaced so that the beams do
not overlap.

Referring to Figs 2 and 3, three light sources
5   42A,42B,42C project three substantially parallel light
beams 44,46,48 from the transmitter unit 10 to the
optic unit 12. The three light sources may comprise,
for example, three optical fibre ends in a known
manner. Alternatively a single light source may be
10   used which produces a plurality, eg three, of parallel
light beams by using optics such as beams splitters and
mirrors.

The optic unit 12 is provided with three spaced
15   retroreflectors 62,64,66. The retroreflectors 62,64,66
reflect the beams 44,46,48 back towards three detectors
68,70,72 located within the transmitter unit 10. These
detectors 68,70,72 may comprise CMOS sensors which
comprise two-dimensional arrays of pixels allowing the
20   position of a light beam on the detector to be
measured. Alternatively a charge-coupled device (CCD)
may also be used in place of the CMOS sensor.
Other types of pixelated image sensors, comprising
image sensors made up of a two dimensional array of
25   pixels, which allow the position of the light beam to
be determined may also be used. Position sensitive
detectors (PSDs) are also suitable. These use the
voltage difference between opposite sides of the
detector to indicates the position of the incident
30   light beam. PSDs may be tuned to work at a particular
frequency and may thus be tuned to eliminate room
lighting effects by tuning it to a higher or lower
frequency than the room lighting. The PSDs are in AC
mode. The incident beam on the PSD is intensity

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modulated and the PSD frequency is turned to that same
frequency. Other types of sensor may also be used, for
example quad cells.

5   As the optic unit 12 moves along its path, the
    positions of the returning light beams 44,46,48 on the
    detectors 68,70,72 will change, due to deviations in
    the movement of the optic unit 12 from this path. The
    use of three retroreflectors 62,64,66 with images
10 laterally displaced with respect to each other enables
    two straightnesses and pitch, roll and yaw to be
    deduced of the optic unit.

    In this example, the motion of the optic unit is along
15 the X axis of the machine, as illustrated in Fig 2.
    Retroreflectors 62 and 64 are located in the optic unit
    12 spaced in the Y direction. The straightness of the
    axis of motion (X axis) of the optic unit is half the
    mean displacement of the change in position of the
20 light beams 44,46 on detectors 68,70 in the direction
    of the axes perpendicular to the directions of motion
    (i.e. Y and Z axes in this case). If, as described
    below, the detectors are located in the optic unit 12
    then the straightness of the axis of motion of the
25 optic unit is the mean displacement of the change in
    position of the light beams 44,46 on the detectors
    68,70 in the direction of the axes perpendicular to the
    directions of motion.

30 If the three light beams 44,46,48 directed towards the
    optic unit 12 are not parallel, a correction must be
    applied to the detector outputs to correct for this
    error. If the beams 44,46,48 are mis-aligned, the
    measurement is corrected from calibration of the two

units 10,12.

The roll of the optic unit 12 is measured by the
differential displacement in the Z direction between
5   these same two beams 44,46 on their respective
detectors 68,70. If the roll centre is located between
the two beams 44,46 then the information from the
detectors 68,70 is sufficient to calculate the roll.
However if the roll centre is off-set, the information
10   from the detectors 68,70 contains both linear and
rotary data and may be no longer sufficient to
accurately calculate the roll. The arrangement of the
present invention has the advantage that as
retroreflector 66 is vertically displaced from
15   retroreflector 62, information from all three detectors
68,70,72 may be used to enable pure roll to be
measured, wherever the roll centre is located.

In order to improve the accuracy of the roll
20   measurement, it is advantageous to use the same
detector to measure the position of the two beams. The
arrangement illustrated in fig 14 enables the deviation
of two light beams 180,182 to be detected by a single
detector 184. The light beams 180,182 are reflected by
25   retroreflectors 186,188 and directed via mirrors and/or
beamsplitters towards the detector 184. A disc 190
provided with an aperture is located in the path of
both beams 180,182 and spins at a rate synchronised to
the capture rate of the detector. Light from each of
30   the beams 180,182 is therefore alternately incident on
the detector 184, producing a chopped signal.
Alternatively, the two beams 180,182 may be modulated
in order to produce a chopped signal.

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The third retroreflector 66 enables the pitch and yaw
of the optic unit 12 to be measured. This third
retroreflector 66 is placed conceptually behind one of
the first and second retroreflectors 62,64 in the optic
5   unit 12. In this example, the third retroreflector 66
is placed vertically above the first or second
retroreflector. This is achieved by vertically
displacing one of the output beams 48 from the
transmitter unit 10 and placing a mirror 54 above one
10   of the retroreflectors 62 to direct the beam 48 towards
the retroreflector 66 placed above the other
retroreflector 64. Pitch and yaw are measured by the
differential displacement on detectors 68,72 between
the two beams 44,48 in the Z and X directions
15   respectively.

This apparatus has the advantage that all six degrees
of freedom may be measured simultaneously.

20   Alternative arrangements are possible in which one or
two light beams are transmitted from the transmitter
unit to the optic unit and split in the optic unit to
create three beams. Fig 13A illustrates a single light
source 150 projecting a beam 152 towards the optic
25   unit. The projected beam 152 is split by beam splitters
154 and 156 into three beams 158, 160, 162. These
three beams are reflected by retroreflectors
164,166,168 towards detectors 170,172,174. This has
the advantage that as common light source is used to
30   create all three beams. Therefore any beam pointing
error is common for all three beams and can thus be
mathematically removed. However the disadvantage is
that there is loss of gain from the displaced beams.
In the previous embodiment, each beam had a gain of two

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at the detector due to the use of retroreflectors.
However, as the beam splitter 154 tilts with movement
of the optic unit, there is only a gain of one at the
detector. For example, for a roll angle of θ, the
5   detector detects a displacement of $L\theta$ in this
arrangement, where L is the distance between the
retroreflectors. In the previous example, with three
outward beams, the displacement was $2L\theta$.

10   As illustrated in fig 13B, this is overcome by using a
second light source 151 which projects a separate light
beam 175 towards retroreflector 166, the reflected beam
being detected towards 174. This maintains the gain on
the roll measurement but has the disadvantage that two
15   separate light sources are used.

Although the measurement of straightness, pitch, roll
and yaw have been described in terms of specific beams
and retroreflectors, it is possible to use all three
20   beams and all three detectors to measure the deviation
in any degree of freedom and hence a generalised
equation can be written as:

Deviation of trajectory from straightline = f
25   $(S_{1x}, S_{1y}, S_{2x}, S_{2y}, S_{3x}, S_{3y}, IR)$
        $= k_1 S_{1x} + k_2 S_{1y} + k_3 S_{2x} + k_4 S_{2y} + k_5 S_{3x} + k_6 S_{3y} + k_7 IR$

where $k_1, k_2 \ldots k_7$ are constants

30   S_{1x}, S_{1y} are positions of beam centre on sensor 1 in
x and y respectively

IR is Interferometry Reading.

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The constants k_1-k_7 are deduced during a calibration procedure and may differ for the deviation in the different degrees of freedom (i.e. straightness, pitch, roll and yaw). Thus a total of 35 constants are

5   deduced during the calibration procedure. (i.e. 7 constants (k_1-k_7) for each of the 5 degrees of freedom).

The k_7IR term in the equation allows non parallel beams to be accommodated.

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It is known in prior art systems for measuring straightness and roll, to use quad cells to detect displacement of a beam. However quad cells have several disadvantages. For a quad cell to be accurate,

15   the beam centre must be aligned with approximately the centre of the quad cell. To improve its linearity range, the quad cells are mounted on motors and must be servoed into the desired position during set-up of the system. In addition the homogeneity of the silicon

20   in the quad cell is poor for the accuracy required in the present system, although servo-controlling the quad cells overcomes this problem to the first order.

Another disadvantage of a non servo-controlled quad

25   cell is that as the beam moves away from the centre of the cell, the linearity decreases. To linearise the non-linear equation relating output to beam centre position, the beam size must be known. Furthermore, if the beam moves wholly into a quadrant of the quad cell,

30   it is not possible to determine its position within that quadrant.

In the present invention, pixelated image sensors such as CCDs, CMOS or CIDs are used. These have several

advantages over the use of quad cell detectors.

A first advantage is that the beam can be detected
anywhere on the pixelated image sensor. As the beam
does not need to be aligned with the centre of the
sensor, there is no requirement for the sensor to be
servoed into position on initial set-up of the system.
Furthermore, the sensor is able to detect the beam
centres even when the beam is on the edge of the
sensor, as will be described in more detail below.

Use of a pixelated image sensor enables the diameter of
the detected spot to be known and in addition allows
the spot diameter of a percentage of the maximum signal
strength to be determined. To determine whether the
spot is at the edge of the sensor, a threshold value
(for example a reading of 100 of a maximum sensor
reading of 4096) is deducted from the sensor reading.
If the pixels between the sensor edge and the spot read
zero, then the spot is not at the edge of the sensor.
If the spot is at the edge, the threshold value may be
increased until the pixels between the spot and edge do
read zero. The spot centre may then be determined. Fig
12A illustrates a spot 140a on the edge of a pixelated
sensor 142. Fig 12B illustrates the spot 140b when a
threshold value has been subtracted. The whole spot is
now on the sensor 142 and its centre may be determined.

The centroid may be calculated in the following manner.
Two images have been detected by the sensor, im1 is the
image with a light beam incident on the sensor and im2
is the image without a light beam incident on the
sensors. The sensor has been calibrated if necessary
to take care of difference in optical response of each

pixel and also to take into consideration their
different areas of sensitivity. This latter could be
done by adjusting the signal level or by using non-
integer indexing values.

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In order to deduce the true signal level im, the two
images im1,im2 are subtracted from each other on a
pixel by pixel bases and a threshold value t is also
subtracted, i.e.:

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$$im_{ij} = im1_{ij}-im2_{ij}-t$$

For all $im_{ij}<0$, the value is set to zero.

15   The centroid may be calculated using a simple
algorithm, by calculating the spatial geometrical
centre.

The x and y coordinates of the centroid for a given
20   threshold t are given by:

$$x_t = \frac{\Sigma i \Sigma S_{i,j}}{\Sigma S_{i,j}}$$

and

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$$y_t = \frac{\Sigma j \Sigma S_{i,j}}{\Sigma S_{i,j}}$$

where s_{ij} is the signal or intensity reading of the
30   i,j^{th} pixel.

This calculation can be repeated for different

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threshold values, to calculate an overall weighted mean
average for the centroid position, i.e.:

$$x= \frac{\Sigma W_t X_t}{\Sigma W_t}$$

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and

$$y= \frac{\Sigma W_t Y_t}{\Sigma W_t}$$

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where w is the weight attached to that particular
threshold value.

For very high threshold values the weighting factor
15   will be small because fewer pixels are involved in
deducing the centroid. For low values of threshold the
weighting factor may also be small because of the noise
associated with deciding which pixels should and should
not be included in the calculation even though these
20   centroid calculations contain the most pixels.

For edge detection one can use the criteria that there
should be at least a row of pixels between the spot and
the edge of the pixelated sensor. If there is not then
25   one used only those threshold values that meet the
criteria.

Alternative algorithms can be used for finding the
centroid of a spot, for example curve fitting
30   algorithms, eg fitting the intensity profile of the
spot to Gaussian or Lorentzian distributions. Other
methods of determining the centroid include finding the

circle of maximum gradient and then finding the centre.
Alternatively the centroid may be determined by finding
the mean position of minimum gradient.

5   Alternatively, if the spot is at the edge of the
     sensor, the centre may be mathematically deduced. For
     example as shown in fig 12C, contours 144,146,148 of a
     percentage of maximum signal strength (e.g. 10%, 20%
     etc) of a spot 140cmay be determined, fitted to
10   circular contours and used to deduce the spot centre,
     using least squares fitting or minimum deviation of the
     minimum maximum radius, for example. This method
     allows the centroid to be deduced, even if not all the
     data is present.
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     Another advantage of using pixelated image sensors is
     that it is easy to map the variation in silicon on the
     sensor. This may be done, for example, by uniformly
     illuminating the sensor and thereby calculating the
20   variation in the silicon as a function of X and Y.

     In prior art autocollimators, a light beam is focused
     onto a spot on a PSD (position sensing detector). A
     change in the angle of the beam causes displacement of
25   the spot on the PSD, whilst linear movement of the beam
     does not. However, use of a PSD has the disadvantage
     of non-homogeneity of the silicon which effects the
     accuracy. It is not possible to use a pixelated image
     sensor in this arrangement as the focused spot has a
30   diameter smaller than a single pixel. However, in the
     method of measuring pitch and yaw in the present
     invention, in which the differential displacement of
     two beams 44,48 on detectors 68,72 is measured,
     pixelated image sensors may be used as the beams do not

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need to be focused to a spot. Therefore this method
benefits from the advantages of a pixelated image
sensor described above.

5   In an alternative embodiment, the third retroreflector
may be actually located behind the second
retroreflector. Fig 5 shows such an arrangement in
which a large third retroreflector 166 is positioned
behind a small second retroreflector 162. The outgoing
10   light beams 144, 148 are arranged such that the beam
148 directed towards the large third retroreflector 166
is not intercepted by the small second retroreflector
162. However this arrangement has the disadvantage that
it adds extra volume to the optic unit 12.

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Another arrangement of the second and third
retroreflectors is shown in Fig 6 in which the third
retroreflector 266 is located behind the second
retroreflector 262. The second reflector 262 has a
20   beam splitter surface 261 and prisms 263 located on its
rear surface to allow some light to pass through it to
the third retroreflector 266 whilst reflecting some
light itself. This arrangement has the disadvantage
that it is relatively expensive, adds volume to the
25   optic unit and some light 265 is lost perpendicular to
the outgoing and incoming beams.

The first arrangement shown in Figs 2 and 3 in which
the third retroreflector is conceptually behind the
30   second retroreflector introduces cross coupling to the
system as the light beams directed to the second and
third retroreflectors are angled to one another. This
arrangement is advantageous as it is a more compact
design, saving volume in the optic unit.

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An advantage of the present invention is that in
addition to enabling 6 degrees of freedom to be
determined along each axis, it also enables squareness

5   to be determined (i.e. the error in the angle of one
axis relative to another).

As previously described with reference to fig 1, the
base 18 of the transmitter unit 10 and a base unit 20

10   mounted on the machine table 14 are provided with
complementary parts of a kinematic support 22 which
enable the transmitter unit 10 to be accurately aligned
along any of the X,Y,Z,-X and -Y axes of the CMM. The
squareness between sets of kinematic supports may be

15   made very precisely so that the transmitter unit can be
accurately aligned with any axis. Alternatively, the
squareness of the kinematic supports may be made less
accurately, with any resulting loss of accuracy i.e.
the error in squareness being accommodated for by

20   calibration. The calibration could be provided, for
example, by comparison of the angles of the transmitted
beams when the transmitter unit is mounted on each
orientation of the base plate, and the known axes from
an accurately calibrated CMM.

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In order to measure squareness, the kinematics between
the base plate and the transmitter unit must either be
precise, so that the axes of the transmitter unit are
square or the error in squareness of the base plate

30   must be known to within a tolerance(i.e. it must have
been calibrated).

The transmitter unit is positioned on the base plate so
that it is aligned with a first axis. The optic axis

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is moved by the quill of the machine away from the
transmitter along this axis, while the straightness is
measured. This is repeated along a second axis.

5   Fig 15 illustrates a graph of measured straightness
     error against the distance travelled by the optic unit
     away from the transmitter unit. Line 92 is the
     straightness along the X axis. In this case the
     transmitter unit is accurately aligned with the X axis
10   line 92 is along the X axis of the graph. Line 94 is
     the straightness along the Y axis. In this case the X
     and Y axes of the machine are not accurately
     perpendicular, so the straightness error along the Y
     axis increases with distance travelled by the optic
15   unit. The angle 96 between lines 92 and 94 is the
     measured machine squareness between the X and Y axes.
     If the kinematics between the base plate and the
     transmitter unit are precise, then this measured
     machine squareness 96 is the actual machine squareness.
20   However, if the base plate has been calibrated for base
     plate squareness errors, this must be taken into
     account in determining the squareness. Angle 98 is the
     squareness error in the base plate and is deducted from
     the measured machine squareness to determine the actual
25   machine squareness 100.

     By measuring squareness between the three axes in
     addition to the six degrees of freedom for each axes, a
     total of 21 degrees of freedom are measured. All 21
30   degrees of freedom are required to calculate the error
     at any point in the measurement volume.
     The light sources (42A,42B,42C in Fig 2) typically
     comprise a diode. However a laser is a heat source
     and lack of thermal stability may cause it to move

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slightly. Movement of the laser causes the beam
pointing to move and thus the beam centroid on the
sensor also moves, which affects accuracy. This
problem is overcome by using an optical fibre to remove
5   the heat source from the light source, as shown in Fig
9. The fibre gives a stable aperture from which the
light is emitted.

Fig 9 shows light from a laser 92 being focused by
10   lens 94 into a first end 96 of an optical fibre 98.
Light emitted by a second end 100 of the optical fibre
98 passes through a mount 102 before being collimated
by lens 104 into a substantially parallel beam 106.
The second end 100 of the optical fibre 98 acts as the
15   launch for the light beam, ie the effective start of
the light beam, with the effect that the launch
(effective light source) (end 100) and heat source
(laser 92) have been separated. Movement of the laser
92 due to heat has no effect on the beam pointing of
20   the light emitted by end 100 of the optical fibre 98.
Furthermore, the mount 102 and lens 104 are provided
with axial symmetry such that they expand evenly and if
there is movement of the mount, it comprises expansion
symmetric about the axis or expansion along the axis
25   rather than tilting movement which would effect the
beam pointing. The mount may be made of all the same
material, so that the coefficient of expansion is the
same throughout. This enables beam pointing stability
of better than a micro Radian to be achieved.
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It is important that the projected light beams do not
twist relative to one another, as this would induce a
roll error. Fig 10 illustrates three optical fibre
ends 110,112,114 mounted on a rod 116. Mounting the

optical fibre ends on the rod has the advantage that a
thermal gradient will not cause the rod to twist and
thus no roll error is induced from this thermal
gradient. The rod 116 may be provided with a hollow

5   core 118 so that it may be cooled by blowing cool air
through the core, thus minimising bowing and
lengthening of the rod.

Each of the optical fibre ends 110,112,114 is mounted

10   on a spherically-shaped portions 120,122,124 of the rod
116. A cross-section of a clamp used to mount each
optical fibre end to a spherical portion is shown in
Fig 11. The clamp 126 has an aperture 128 into which
is inserted a spherical portion 120 of the bar. There

15   are three points of contact 130,132,134 between the
clamp 126 and spherical portion 120 which enables the
clamp to be tilted about X,Y or Z before being secured
by tightening screw 136. The optical fibre ends
connected to the clamps may therefore be adjusted about

20   X,Y and Z to point the beams in the desired direction.

If a single optical fibre and a combination of mirrors
and beamsplitters are used to produce the three light
beams, the optical fibre, mirrors and beamsplitters may

25   be mounted on the bar in a similar manner.

Other optical elements, such as the detectors, may be
mounted on the rod. An optical element, such as an
optical fibre or detector, may be mounted out of the
30   plane of the others by mounting it to the bottom rather
than the top of a clamp.

In order to accurately determine the centre of the
optical beams 44,46,48 on their respective detectors

23

68,70,72, the beams are required to have minimal stray
reflection components. However in practice it is
difficult to remove the interference patterns caused by
the collimating lenses and retroreflectors. To reduce
5   these effects an incoherent light source is required,
however it is difficult to collimate an incoherent
light source to the required level of this apparatus.
This problem is partially solved by using a coherent
light source which is intensity modulated over time to
10   cause frequency variation. The relevant time interval
for the intensity modulation is the exposure time for a
given pixel in the detector.

There is a minimum exposure time for a given pixel in
15   the detector. For example, if the exposure time for a
given pixel is 10µs and the intensity is measured to an
accuracy to within 1%, then without locking the
exposure time to the intensity modulation signal, the
light source may be modulated to greater than 10MHz to
20   have the desired effect.

The coherent light source may be intensity modulated by
other means. For example, the light may be passed
through an optical fibre which is wound around a
25   piezoelectric material. Pulsing the piezoelectric
material causes its diameter to change, resulting in
variation in the optical length of the optical fibre
and hence modulation of the light beam thus reducing
its coherence length.
30

Self interference of the beam caused by thin optics in
the light path produces interference patterns on the
image. This is caused when some light passes straight
through the optics whilst other light is doubly

reflected to the back and front faces. This may be overcome by using two light sources to produce the light beam which preferably have different wavelengths and/or are modulated at different frequencies. The

5   light beam is thereby caused to beat a high frequency which produces a short coherent length. This technique also helps remove a speckle pattern on the image caused by dust and general point defects.

10   Self interference of the beam caused by double reflecting on thin optics as described above is illustrated in fig 8A and may be avoided by using wedged optics as illustrated in Figs 8B and 8C. In fig 8A a thin plane optical element 81 is place in front of

15   a sensor 83. A light beam 80 is incident on the plane optical element 81. Part of the light beam 80 passes straight through the optical element to the sensor, whilst another part of the light beam 83 is doubly reflected by the optical element and interferes with

20   beam 80 to form large fringes on the image. In Fig 8B a wedged optical element 82 having a large wedge angle is placed in front of a sensor 83. A light beam 80 is incident on the wedged optical element 82. Part of the light beam 86 passes straight through the optical

25   element to the sensor 83, whilst another part of the light beam 88 is doubly reflected by the optical element and passes out of the optical element at an angle such that it misses the sensor 83. In Fig 8C, the wedges optical element 84 has thin wedge angle so

30   that the double reflected beam 90 approaches the sensor 83 at a small angle to the beam which passes straight through 86 to produce many narrow fringes which have only a small effect on the image.

25

Room lighting has been found to have an effect on the
detection of the beam centres incident on the
detectors. For example, the background lighting causes
the image to flutter. In order to remove this effect
5   the image capture period of the detectors needs to be
synchronised to the room lighting, eg to mains
frequency. In addition, to remove the effect of room
lighting two images are required, one with the return
beam present and one without. The difference between
10   the two images is used to calculate the centroid.

Pixelated image sensors have a saturation level at
which intensity against sensor output becomes non
linear. If the detected light from the light beam is
15   close to the saturation level of the sensor, there will
be a non-linear response and this must be taken into
account when subtracting background light.

Other solutions are possible to minimise the effect of
20   background lighting. In one such solution, a narrow
bandpass filter is positioned in front of the sensors.
This transmits only the wavelength of the light source
and rejects other wavelengths, i.e. background light.

25   In a second solution, a neutral density filter is
placed in front of the sensors. This transmits only a
certain percentage (e.g. 10%) of all incident light
(i.e. both from the light source and background light).
By increasing the intensity of the light source, the
30   intensity of the light source relative to the
background light is increased.

In a third solution the detectors are shaded, for
example by placing them behind apertures or tubes to

minimise the effect of background light. This may also
be used for the retroreflectors, with the advantage
that if more than one beam uses a retroreflector, stray
light is reduced.

5

In another solution, the integration time of a
pixelated sensor is chosen to reduce the effect of the
background light. For a certain integration time of
the sensor, the background light appears static, giving
10   uniform background illumination. This integration time
of the sensor will depend on the frequency of the
background light. The optimum integration time of the
sensor for a particular background condition may be
determined by cycling through different integration
15   times on the sensor and looking at the detected beam
centroid. The integration time which causes the least
distortion of the beam centroid is chosen. This
solution has the advantage that it reduces the need for
filters.

20

In the preferred embodiment, the optic unit contains
only optical elements i.e. retroreflectors and mirrors.
This ensures that measurements are not affected by
dragging cables etc, affecting the movement of the
25   optic unit which is mounted on a moving machine
component. In this apparatus the detectors and light
sources to which trailing leads are associated are all
located in the transmitter unit which is mounted on a
fixed machine component. Where the coordinate
30   positioning apparatus is a machine tool, the optic unit
may be mounted on the spindle and the transmitter unit
may be mounted on the machine bed. The machine bed is
very big and heavy which results in the trailing leads
on the transmitter unit having very little affect on

27

the movement of the transmitter unit. Conversely
trailing leads on the optic unit which is mounted on
the spindle would affect its movement and thus the
accuracy of the system.

5

The invention is not limited to the embodiment in which
the optic unit contains only optical element. Fig 7
shows an embodiment in which the detectors 68,70,72 are
located in the optic unit 12. However this embodiment

10   has the disadvantage that both units have trailing
leads (i.e. leads to the light source in the
transmitter unit and to the detectors in the optic
unit). These trailing leads may effect the accuracy of
the system.

15

An advantage of the present invention is that it is not
limited to taking measurements when both units are
stationary. Such a stepwise method of moving the optic
unit to a new position, taking the measurement when

20   stationary, and then repeating at a new position is not
time effective. The current invention allows images to
be taken whilst the optic unit is in motion.

The detectors require time to detect the image, to

25   allow the image to be processed and a signal created.
The images detected whilst the optic unit is in motion
will be blurred. These images are averaged over the
distance moved by the optic unit.

30   The signals from the detectors will be noisy due to air
turbulence, whether the units are moving or stationary.
This is overcome by parametrically fitting the data.
For example the straightness reading s_x may be fitted
to a quadratic curve, as illustrated below.

28

$$S_x = a + by + cz^2$$

Time-averaging may be required for the readings taken
by the interferometer due to air turbulence, for
example.

Although in a preferred embodiment three detectors and
three parallel beams are required to detect deviations
in all five degrees of freedom, only two detectors and
two parallel beams are required in the apparatus to
detect deviations in any one plane.

It is also possible to have a system of more than three
beams, retroreflectors and detectors. For example, two
retroreflectors may be positioned side by side, as in
the above example, each of the two retroreflector
having another retroreflector positioned conceptually
behind them, to make a total of four. This arrangement
provides more data to be average, improving accuracy.

The transmitter unit should advantageously be aligned
with an axis of the machine so that as the optic unit
is moved along an axis of the machine, the projected
beams stay centred on the detectors. However, it may be
difficult to accurately align the base plate, on which
the transmitter unit is mounted, with the machine axes.
Fig 16A illustrates the transmitter unit 10 and the
optic unit 12 which are positioned at an angle to the X
axis of the machine axis. Light beams 102,104,106 are
therefore projected from the transmitter unit at an
angle to the X axis. As shown by fig 16B, when the
optic unit 12 is moved along the X axis, the position
of the incident beams 102,104,106 relative to the optic

unit 12 changes, which will result in movement of the spots on the detectors and may cause the spots to move completely off the edge of the detectors.

5   As the position of the spot on the detector is known, this information may be used to change the vector of travel of the optic unit such that the spots remain centred on the detectors.

10   In a first step the optic unit is moved along the machine axis. This movement may be a predetermined distance or until the spots move off the edge of the detectors. Then, using information of spot position on the detector, the machine quill, on which the optic

15   unit is mounted, is servoed to bring the spots back to the centre of the detectors. As the original position (x_1, y_1, z_1) and the new position (x_2, y_2, z_2) of the optic unit and the distance travelled between them are known, the vector along which the optic unit should travel to

20   keep the spots centred can be determined. The optic unit may be driven along this axis in a smooth or in a stepped manner.

     Once this vector has been determined for one axis, the

25   same vector can be used for all other axes. If the vector is determined separately for each axis, then in order to determine squareness the vector, base plate squareness error and measured errors must all be known.

30   The problem of misalignment of the transmitter unit with respect to the machine axes may also be overcome by adjustment of the base plate. The base plate on which the transmitter unit is mounted is preferably provided with an adjustment mechanism for adjusting the

position of the transmitter unit in pitch, roll and
yaw. A possible mechanism for the adjustable base
plate is described in PCT application no
PCT/GB03/000175.

5

As in the previous method, the optic unit is moved
along the machine axis. This movement may be a
predetermined distance or until the spots move off the
edge of the detectors. The position of the spots on
10 the detectors is known and using this information, the
angle of the base plate is adjusted until the spots
return to the centres of the detectors, thereby
aligning the transmitter unit with the machine axis.
Feedback from the detectors is used to inform the user
15 about which axes the base plate should be adjusted and
by how much. This could either be a manual adjuster,
or the base plate adjustment mechanism may be motorised
so that the base plate is adjusted automatically using
feedback from the camera. In the latter case, the
20 motors are used in this alignment procedure and then
turned off.